Rainfall variability and groundwater availability for irrigation in Sub-Saharan Africa: evidence from the Niayes region of Senegal

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1 February 2018

Rainfall variability and groundwater availability for irrigation in Sub-Saharan Africa: evidence from the Niayes region of Senegal

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Abstract

Recent research on climate change, within the context of Sub-Saharan Africa, has shown the vulnerability of groundwater resources to climate change and variability. In Senegal, agriculture is among the most important users of groundwater resources, especially in the northern coastal area called 'Niayes' where farmers practice irrigated agriculture and use almost exclusively the quarternary sand aquifer for their irrigation needs during the dry season – which is the main growing period. However, in Senegal, irrigated agriculture, particularly that of horticultural crops, mostly grown in the Niayes, has attracted less research attention in terms of studies focused on climate change or variability, compared to staple-growing rainfed regions. In the Niayes region, farmers grow most of Senegal's horticultural production. Combined with human use of water resources, climate variability may threaten future irrigation water availability in the area.

This paper uses an integrated hydroeconomic model and a rainfall generator to evaluate the impact of rainfall variability on irrigation water availability and simulate its implications on producers' responses and groundwater management policy measures.

Results show that groundwater availability is diminishing over time, resulting in higher water table depth and smaller water withdrawals by farmers who will tend to decrease the area allocated to crops and favor the higher-valued crops. These trends are accelerated under a drier climate regime. A taxation policy to stabilize the aquifer would induce a reduction of the area under cultivation and have negative implications on revenues. Supply-side measures to enhance recharge may not be technically or financially feasible. This suggests that Senegal needs to develop groundwater management options that favor sustainable use of agricultural water resources without hindering national horticultural production.

Key Words: Agriculture; irrigation; rainfall variability; hydro-economic modeling; groundwater management; Senegal.

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INTRODUCTION

Ground and surface water resources are vulnerable to climate change and variability as well as extreme events (Kumar, 2012; Booker, 1995; Tanaka *et al.*, 2006; Bates *et al.*, 2008 ; ...). In Sub-Saharan Africa (SSA) groundwater constitutes an important source of consumptive water use in most countries. However, despite its importance and changing climate conditions in the region, there has been historically little interest in analyzing the impact of climate change and/or variability on groundwater availability (Taylor, Koussis and Tindimugaya, 2009). The conference on « Groundwater and climate in Africa »[3] held in Kampala (Uganda) in June 2008 has been the first one on these issues in Africa (Taylor, Koussis and Tindimugaya, 2009). Since then, there has been a growing number of scientific publications on interactions between groundwater and climate related changes (see Taylor, Koussis and Tindimugaya, 2009; Nyenje and Batelaan, 2009 for examples).

Agriculture is one of the biggest users of groundwater resources along with domestic and industrial sectors. However, in SSA, climate related studies on groundwater resources have mostly focused on the resource (see examples in Hughes *et al.*, 2015) and not sufficiently on the implications of climate shocks on agricultural production and producers' responses. Most of the studies have focused on modeling hydrological aspects without an explicit integration of user behavior (e.g. Nyenje and Batelaan, 2009). Indeed, by considering water demand as a fixed amount, hydrological models fail to capture the economic value of water (see Harou *et al.*, 2009) and do not fully account for users' response to groundwater availability under climate change and variability. On the other hand, studies focusing on climate impact on agriculture have extensively focused on rainfed agriculture (Roudier *et al.*, 2011; Roudier, 2012; Jalloh *et al.*, 2013; Sultan and Gaetani, 2016), mostly due to its widespread practice compared to irrigated agriculture that only constitutes less than 5% of arable land in SSA (Giordano, 2006). They have therefore not sufficiently studied the interactions between climate and irrigated agriculture.

This situation is observed in West African countries like Senegal, where, almost all the studies on climate impact on agriculture have been oriented towards staple crops in rainfed regions (P Roudier et al., 2014; Sene, Diop, & Dieng, 2006) with a poor focus on irrigated crops like horticultural ones mostly grown in the coastal area called Niayes that represents one of the two main agroecological zones of irrigated agriculture in Senegal. In the Niayes, farmers almost exclusively use the quaternary sand aquifer for irrigation and are impacted by rainfall variability mainly through groundwater availability as shown by previous climate related studies in the region (Aguiar, Garneau, Lézine, & Maugis, 2010; Dasylva & Cosandey, 2005). Those hydrological and geographical researches have been interested in how past climate have affected the aquifer and generally point out a negative effect of climate on aquifer recharge and depth (Aguiar *et al.*, 2010; Dasylva and Cosandey, 2005). However, little effort has been done towards assessing the future impact of rainfall variability on water resources in the area and how changes in physical variables might affect horticultural production, farmers' revenues and their responses as well as the implications for groundwater management.

This paper aims at filling this gap by developing an integrated hydroeconomic model (HEM) that allows to analyze the impact of climate variability on irrigation water availability and its implications on production and agricultural water management in the Niayes area of Senegal. The ability of integrated hydroeconomic models to do such analyses has been shown in Western countries (Medellín-Azuara, Howitt and Lund, 2010; Blanco-Gutiérrez, Varela-Ortega and Purkey, 2013; Howitt *et al.*, 2012; Varela-Ortega *et al.*, 2016; Esteve *et al.*, 2015; ...) and some SSA countries (see You and Ringler, 2010; Robinson, Willenbockel and Strzepek, 2012 for examples in Ethiopia). In West African countries such as Senegal, to date, there has

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[3] http://www.gwclim.org/

been no application of HEM to assess climate change or variability impact and adaptation on agricultural water resources despite their suitability for this type of analysis.

The objectives of the paper are threefold : (1) to assess the effect of rainfall variability on aquifer levels; (2) to assess the implications on farmers' water extractions and cropping pattern; (3) to analyze different water management instruments, namely, the imposition of a volumetric water tax (demand-side instrument).

Our integrated hydroeconomic model is mostly composed of a hydroeconomic component representing aquifer dynamics and groundwater use behavior, a bioeconomic model to derive agricultural water demand reflecting the economic value of water. To this combination, we associate a stochastic annual rainfall generator.

In the next section, we present the study area focusing on agricultural activities, the characteristics of the aquifer under study as well as the climate in the region. In section 3, we describe our methodology. Section 4 describes the data we used. Section 5 discusses key results and alternative policy interventions while discussing their implications. In section 6, we discuss the results in light with the body of literature on the issue. Lastly, section 7 concludes the paper and discusses research perspectives for better policy design based on identified limitations of the study.

2. AGRICULTURE, GROUNDWATER AND CLIMATE IN THE NIAYES AREA

The Niayes area is the coastal zone located in the North-West of Senegal riding between four administrative regions: Dakar, Thiès, Louga and Saint-Louis (see figure 1).

Agriculture is the main economic activity with two growing seasons, the rainy season that goes from June to September with a minimum mean annual rainfalls of 138mm and a maximum of 599mm in the period 1970-2011 and the dry season from October to May. Due to low level of annual rainfalls, farmers specialize in irrigated agriculture during the dry season that is the main growing season[4] during which are grown most of horticultural crops in Senegal. The Niayes is the main production area of horticultural crops with "half to two-thirds of the national production of fresh vegetables" (Fare et al., 2017). Irrigated area covers 10000ha (J. Faye, Ba, Dieye, & Dansoko, 2007) with around 10000 horticultural producers (Ministry of Agriculture and Rural Equipment, 2013). In the Niayes, farmers use the quaternary sand aquifer for irrigation needs, to which they access mostly through private wells (shallow wells, dugwells and increasingly tubewells) by manual or mechanical extraction (with motorized pumps)—(Ministry of Agriculture and Rural Equipment, 2013). There is a small proportion of farmers (less than 3%) in the South of the Niayes that access water through the Senegalese water company (SONES). Therefore, water costs faced by the farmer mostly reflects the cost associated with water extraction which is the energy cost of pumping for farmers using mechanical extraction and investment cost for well construction. More details on agricultural activity in the area can be found in Fare *et al.*, (2017) who did an extensive analysis of the agrarian system in the Niayes.

Concerning water resources management, it is under the responsibility of the direction of management and planning of water resources (the DGPRE[5]) embodied in the Ministry of hydraulics and sanitation. To date, very little is known about the agricultural water withdrawals within the Niayes area given that the farmers' private wells are currently neither subject to effective control from the DGPRE nor under any significant regime of community-level water resource management (to the best of our knowledge). However, there does exist a water code designed in 1981 and according to which farmers extracting more than 5m^3 of ground water per hour should pay for the water they use up to 12.12Fcfa per cubic meter.

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[4] Due to climate change and variability, the duration of the seasons may be variable.

[5] Direction de la gestion et de la planification des ressources en eau.

However, this pricing scheme has not been revised since 1980s. Therefore, the DGPRE is currently undertaking studies to review this water pricing scheme and explore new possibilities of water governance. We hope that this paper will contribute to their pricing analysis, as well as to the larger debate around the appropriate type of water resource management regime to impose on the region.

The quaternary sand aquifer is an unconfined aquifer that covers a surface of 2300km^2 (Aguiar et al., 2010). It is mainly recharged by rainwater infiltration (Aguiar *et al.*, 2010; Dasylva and Cosandey, 2005). However, since the droughts of the 1970s and 1980s, rainfall levels have remained below the levels reached during wet periods (before 1970s). On average, rainfall has decreased from 500 mm in the 1932-1960 decades (Ndong, 1995) to 321.42 mm in the period 1970-1990 and 353.67 mm in the period 1990-2011.

Therefore, if warming trends and (more importantly) lower rainfall levels persist, the groundwater recharge may decrease and lead to declines in the available stock of groundwater. This might be exacerbated by growing extractions due to predicted warmer temperatures (Jalloh *et al.*, 2013) in Senegal that will tend to increase the evapotranspiration of crops and, therefore, induce greater demand for irrigation water. In addition, the aquifer is used by other actors like industries, the Senegalese Water Company[6], the entity that extracts and distributes water to some industries and rural households via boreholes. This raises concerns about irrigation water availability under different climate outcomes and how the agricultural sector can cope with a degrading resource base that is the primary production factor for farmers in the Niayes region.

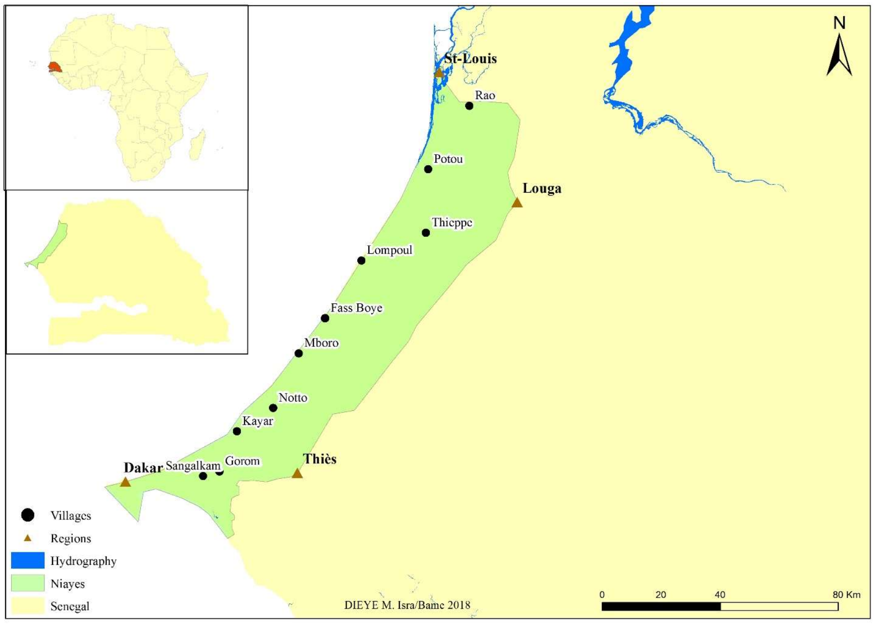

Figure 1: The Niayes area of Senegal

Source: Realized by Dieye (2018)[7]

3. AN INTEGRATED HYDROECONOMIC MODEL TO ASSESS GROUNDWATER AVAILABILITY AND MANAGEMENT UNDER CLIMATE VARIABILITY

There is an extensive literature on the theoretical framework of common pool resources (Burt, 1964, 1966, 1967; Kim *et al.*, 1989; Ostrom, 1990; Koundouri, 2004). This has oriented

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[6] This usage is applicable to the period during which the primary data was collected (in 2014). However, there may have been changes since then and the company's withdrawals may have diminished over time.

[7] Dieye is a geographer at the Senegalese Institute of Agricultural Research.

our understanding of the basic problem of agricultural groundwater use, before putting it within the specific context of the Niayes region of Senegal. Empirically, economic modeling of groundwater has been mainly done using integrated hydroeconomic models that are extensively reviewed in Harou *et al.* (2009). There is a growing number of empirical studies on water availability under climate change or variability and its implications on agriculture and water management that use integrated hydroeconomic models (Medellín-Azuara, Howitt and Lund, 2010; Blanco-Gutiérrez, Varela-Ortega and Purkey, 2013; Howitt *et al.*, 2012; Varela-Ortega *et al.*, 2016; Esteve *et al.*, 2015…). Based on this literature, we tailor the integrated hydroeconomic modeling framework in Msangi and Cline (2016) to our area of study and research objectives.

Integrated HEM are of two types: holistic or modular (R. Brouwer & Hofkes, 2008). According to Brouwer and Hofkes (2008), the holistic approach consists of a single, integrated model which allows for direct interaction between components, whereas the modular or compartmentalized approach is comprised of stand-alone components which more loosely interact, with simulation outputs from one component providing the inputs for another one to use. In our case, unlike the holistic approach build in Msangi and Cline (2016), our integrated HEM follows a modular approach (see Brouwer and Hofkes (2008) for more details in modular and holistic approaches and Esteve *et al.*(2015) for an application of modular approaches) which is composed of two stand-alone models: a hydroeconomic model and a bioeconomic farm production model calibrated using the standard PMP approach (Howitt, 1995). These models, implemented in GAMS, are run separately but communicate via variable exchange with output variables from one model being input variables in another model as we will later explain it in detail. To this set of models we associate a stochastic rainfall generator inspired by Safouane *et al.* (2016).

The farm production model is run first to obtain the per hectare irrigation water demand that reflects the implicit marginal value of water to the agricultural producer. This water demand function is then transformed into a measure of producer benefit which becomes part of the decision maker's objective criterion within the hydroeconomic model. This latter directly captures the groundwater management decisions and outcomes by combining the economic benefit of water withdrawals (net of pumping costs) and the resulting aquifer dynamics from period-to-period. We can choose between alternative management regimes in which we can, in one case, account for just the immediate costs of pumping groundwater (the myopic case) or, alternatively, we can also take into account the implicit 'social' user cost of groundwater extraction, which captures the externalities a forward-looking decision-maker would consider in a dynamically optimal resource management regime. The simulations from this hydroeconomic model provides us with aggregate levels of water availability and farmers' groundwater use (aquifer level and withdrawals) over time, for the entire irrigated area in the Niayes. Withdrawals are then re-scaled to per ha quantities and fed into the farm model to evaluate the impact of different water availability levels on farmers' net revenue and their responses in terms cropping pattern. Finally, the solution of the (dynamically-optimal) resource problem defines the benchmark for economic efficiency that we will use as a basis for comparing alternative policy measures, in a later sub-section of the paper. The overall framework that we use to capture the key linkages between the different models is captured in Figure 2. In the following sub-sections, we describe the structure of the models and the results from our scenario-based simulations.

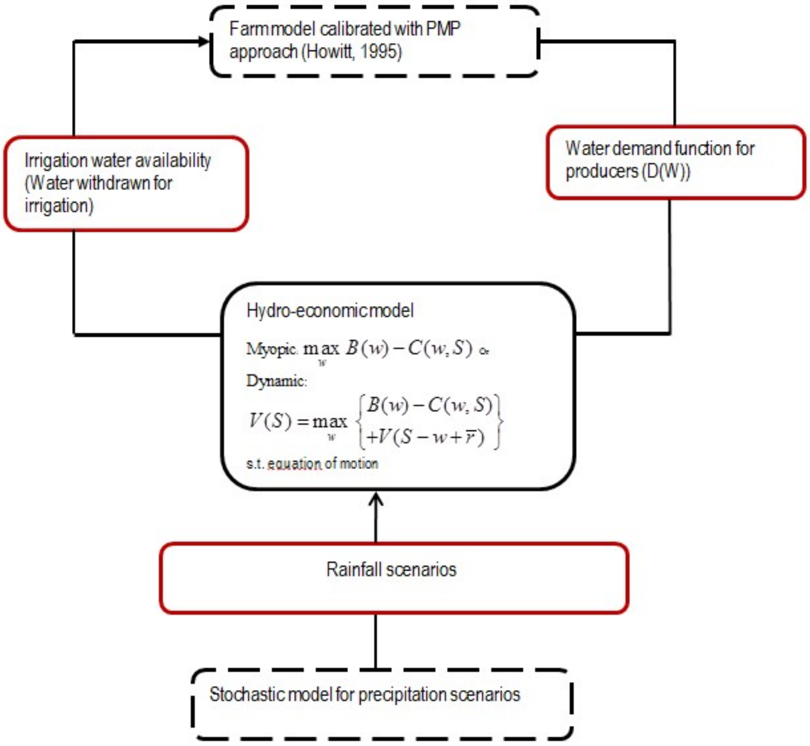

Figure 2: Model integration

Source: Authors

3.1. Hydro-economic modeling framework

3.1.1. Aquifer dynamics and choice of a single reservoir

In the Niayes area, we noticed spatial heterogeneity for parameters such as the infiltration rate of rainfalls and the depth of the water table. As in Msangi and Cline (2016), the ideal would be to divide the aquifer into several interconnected reservoirs to account for that heterogeneity. However, we do not have the necessary data to estimate the connection coefficients between sections of the aquifer nor do we have sufficient data on hydrological parameters such as infiltration rates for the entire area. For this reason, we are constrained to consider the aquifer as a single reservoir as illustrated in figure 3.

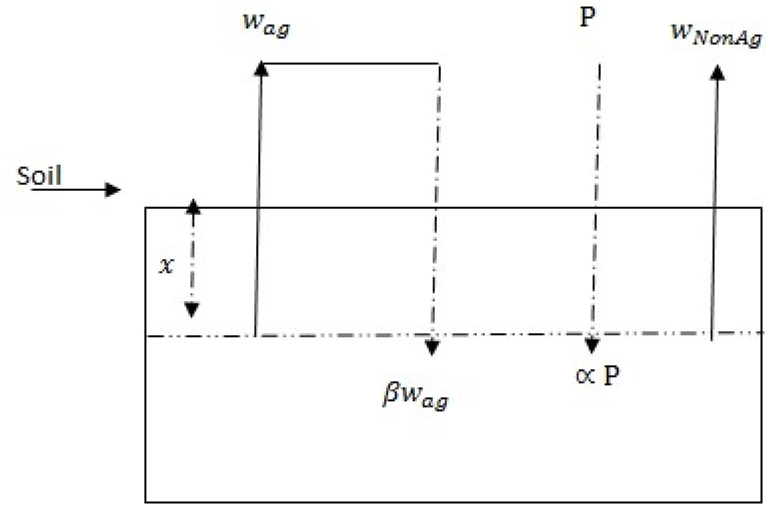

Figure 3: Aquifer dynamics
Source: Authors

We capture aquifer dynamics by considering inflows (recharge) and outflows (withdrawals from agricultural and non-agricultural users). Inflows are mainly represented by rainfalls for which only a share $\propto$ infiltrates the soil as recharge. Indeed, due to factors such as evaporation, soil characteristics, vegetation and others, not all the rain that falls goes to the aquifer. In addition to inflows from rainfalls, we consider inflows from irrigation water applied to crops which represents a share (β) of farmers' withdrawals (w_{ag}). Therefore an outflow for irrigation needs of $\mathrm{w_{ag}}$ will result in a return to the aquifer of $\beta \mathrm{w_{ag}}$. However, this return rate is not available for our area of interest. Therefore, since studies have been undertaken to evaluate the infiltration rate of rainfall (Gaye, 1990; Faye, 1995; El Faid, 1999; Tine, 2004; Dasylva and Cosandey, 2005), we consider that the return to the aquifer β is equal to the infiltration rate $\propto$. Sensitivity analyses are conducted in this paper to see how our results vary according to some parameters, including the infiltration rate. Apart from agricultural withdrawals, we account for non-agricultural users' (water company and rural populations through boreholes) water extractions (w_{NonAg}) for whom we do not consider any return to the aquifer as it is primarily for potable water supply in urban areas and for domestic water use in rural areas. We consider non-agricultural withdrawals as exogenous quantities in our model.

The equation of motion that describes aquifer dynamics is written as follows:

$$x_{\mathrm{t+1}} = x_{\mathrm{t}} + \frac{w_{ag} * 10^{-4}}{As_y} - \frac{\propto w_{ag} * 10^{-4}}{As_y} + \frac{1}{As_y} w_{NonAg} * 10^{-4} - \frac{\propto \mathrm{P} * 10^{-3}}{s_y} \qquad (1)$$

Where x_{t} *and* $x_{\mathrm{t+1}}$ (in meters) correspond to the aquifer lift in the current and future periods respectively. A is the area covered by the aquifer. In order to avoid inconsistencies in the units of the variables, we need to convert volumetric values (w_{ag} and w_{NonAg}) into consistent units of measure (i.e. meters) according to the following conversion rule: when we apply one millimeter of water to a surface, it covers 10^{-3} m^3 /m^2 (C. Brouwer, Goffeau, & Heibloem, 1985). This means that each unit of m^3/ha withdrawn from the aquifer leads to an increase of the aquifer lift of 10^{-4}m. This explains the division of withdrawals by the total area of the aquifer and the multiplication by 10^{-4}. We also multiply precipitation levels by 10^{-3} in order to convert millimeters into meters. s_y is the specific yield, a coefficient that allows to account for the amount of water released from the aquifer (see Johnson (1967) for a formal definition of specific yield).

The economic benefits for groundwater can now be combined with the representation of aquifer dynamics, to give a complete framework for looking at the impact of (economically-driven) groundwater extraction on the aquifer underlying the Niayes region. The overall optimization problem that determines withdrawals over time can be either myopic or forward-looking in perspective, as we show in the following sub-sections.

3.1.2. Myopic optimization

As explained in the literature (Gisser & Sánchez, 1980; Griffin, 2006; Knapp & Olson, 1995; Wang & Segarra, 2011), when it comes to economic modeling of groundwater, the myopic behavior is a situation in which each agent maximizes its own profit to choose the amount of water he/she withdraws without accounting for the availability of the resource in the future and regardless of what the other agents will do. The maximization program in equation (2) displays the myopic behavior in the case of one reservoir at the regional scale (the Niayes region):

$$\underset{w_{ag,t}}{\text{Max}}\{[\pi(x_t, w_{ag,t}) = SirrB(w_{ag,t}) - C(w_{ag,t}, x_t)]\} \qquad (2)$$

S.t.

$$x_{\mathrm{t}+1} = x_{\mathrm{t}} + 10^{-4}\frac{((1-\propto)w_{ag,t}+w_{NonAg})}{As_y} - \frac{\propto \mathrm{P_t} 10^{-3}}{s_y} \qquad (3)$$

Where t corresponds to one period that we consider equal to a year. $B(w_{ag,t})$ is the per hectare benefit from extracting $w_{ag,t}$ of water. $Sirr$ is the total irrigated area in the Niayes.

The empirically-derived demand for water D($\boldsymbol{\lambda}_{water}$) -- or, rather, its inverse $\boldsymbol{\lambda}_{water}(w)$ – is used to obtain the benefit function for groundwater withdrawals (i.e. $B(w) = \int \boldsymbol{\lambda}_{water}(w)dw$). The Lagrange multiplier $\boldsymbol{\lambda}_{water}$ represents a representative producer's willingness to pay for one more unit of water which corresponds to the marginal profit resulting from using one more unit of water.

$C(w_{ag,t}, x_t) = x_t * \mathrm{c} * w_{ag,t}$ is the extraction cost of $w_{ag,t}$ of water (4)

c is derived from the first-order condition of the maximization program:

$$\partial\pi(x,w)/\partial w = Sirr * \partial B(w)/\partial w - \partial C(w,x)/\partial w = 0 \Rightarrow Sirr * \mu w^{\theta} - x * \mathrm{c} = 0$$

$$\mathrm{C} = Sirr * \mu w^{\theta}/x \qquad (5)$$

where μ and θ are respectively the constant and the **elasticity** of the demand function.

We do not observe farmers' withdrawals (w_{ag}). To estimate them, we consider the per hectare water use in the farm model $\sum_j w_j/\sum_j \propto_j$ (see data section for more information on the water use data by the representative farm) that we multiply by the total irrigated area in the Niayes (Sirr).

$$w_{ag} = Sirr * \sum_j w_j/\sum_j \propto_j ==> \mathrm{c} = Sirr * \frac{\mu(Sirr*\sum_j w_j/\sum_j \propto_j)^{\theta}}{x} \qquad (6)$$

3.1.3. Dynamic optimization

In this case, the net present value of current and future net benefits from groundwater extraction are maximized at the regional level as in the following program:

$$V(x) = \underset{w_{ag,t}}{\text{Max}} \left\{ \begin{array}{c} \pi(x_t, w_{ag,t}) + \delta V(x_{t+1}) \\ s.t. \\ x_{t+1} = x_t + 10^{-4} \dfrac{((1-\propto)w_{ag,t} + w_{NonAg})}{As_y} - \dfrac{\propto P_t * 10^{-3}}{s_y} \end{array} \right\} \tag{7}$$

Where, δ is the discount rate. The other terms of this maximization problem have the same meaning as in the myopic case. To solve this dynamic problem, we use a Chebychev polynomial to approximate the infinite-horizon, carry-over value function of the Bellman equation (Howitt, Msangi, Reynaud, & Knapp, 2002; Hubbard & Saglam, n.d.).

3.2. The farm model to derive the demand for groundwater

Different methods of deriving agricultural water demand exist as describes Graveline (2016) in his review on water programming models. In summary, econometric and programming methods are the most used to derive irrigation water demand by agricultural economists (Graveline, 2016). Econometric methods consist of establishing a relationship between observed water consumption and data on the perceived cost of water (Bontemps & Couture, 2002). In our case, we could not get accurate data on producers' water consumption and, consequently, were compelled to use an alternative approach. Mathematical programming models capture the water usage behavior of a representative farmer maximizing his profit by making choices over the optimal combination of productivity-enhancing inputs – which include water. The profit depends on the cost of inputs and the revenues from production. Those revenues depend on i) crop yields represented by an explicit production function (Graveline, 2016) depicting the yield response to water, ii) the area allocated to crops and iii) crop prices. Different types of production functions have been used to represent the yield-water relationship as summarized in Graveline (2016). In our model, the choice of a production function has been guided by the calibration process as we will explain later in this sub-section.

Our farm model depicts a typical producer that maximizes its profit according to neoclassical microeconomic theory. In the context of the Niayes, we assume that a representative horticultural producer maximizes its profit π from horticultural crops[8] under resource (land, labor and water) availability constraints as shown in equations 8 to 13.

$$\underset{z_{ij}, w_j, a_j}{\text{Max}} \left\{\pi = \sum_j \left[a_j\left(y_j(w_j) * p_j\right) - \left(\sum_i z_{ij} * c_{ij}\right)\right]\right\} \tag{8}$$

$$\sum_j a_j \leq A, \quad (\lambda_{land}) \tag{9}$$

$$\sum_j z_{famlabj} \leq totalfamlab, \quad (\lambda_{famlab}) \tag{10}$$

$$\sum_j z_{paidlabj} \leq totalpaidlab, \quad (\lambda_{paidlab}) \tag{11}$$

$$\sum_j z_{ij} \leq totalinputi, i \neq (famlabj, paidlabj, w), \quad (\lambda_{inputs}) \tag{12}$$

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[8] Although most small-holder farmers in Senegal are typical of other farm households in developing countries that subsist partially (or wholly) on what they produce on-farm – the horticultural growers in the Niayes are more commercialized and profit-oriented. Therefore we assume separability between the consumption and production decisions in the output market, and focus on the production side of the farmer's problem.

$$\sum_j w_j \leq w_{agt}, \quad (\lambda_{water}) \qquad (13)$$

Where, $\boldsymbol{\pi}$ is the profit of a representative producer ; j represents crops (onion, carrot, cabbage, sweet pepper, eggplant, african eggplant, tomato); a_j represents the area allocated to crop j ; y_j the production function of crop j ; w_j is the amount of water applied to crop j ; p_j is the price of crop j**;** i is the index of inputs (mineral and organic fertilizer, pesticides, labor, water); z_{ij} represents the vector of input quantities; c_{ij} is the vector of unit input cost except water. Water cost is accounted for in the hydroeconomic model as we will explain below. $\overline{A}, \overline{X}$ and $\overline{W}$ correspond to the available quantities of key resources used in production.

Equations (9) to (12) represent land availability constraint, family labor constraint, paid labor constraint, other inputs constraint (mineral and organic fertilizer, pesticides). Input constraints are split into labor constraint (10 & 11) and other inputs constraint (12). Constraint 12 would apply to those inputs which are limited at the household/firm-level, such as labor – whereas other inputs can be purchased freely on the market without any explicit rationing. For family labor, it is considered as a resource available to the household which the farm does not pay for. Equation (13) represents a constraint on available water, meaning that applied water depends on available water $(\overline{W})$ from groundwater resources that correspond to farmers' withdrawals. In Mathematical Programming approaches, water can be explicitly priced (on a volumetric basis) or else provisioned under a quantitative limit or at some extraction cost. The extraction cost of water, integrated in our hydroeconomic model, is the only water-related cost that we account for in the Niayes case as farmers mostly access water through private wells.

We calibrated the model to observed data by using the standard PMP approach of (Howitt, 1995). There is a comprehensive discussion on the standard PMP approach, its limitations and subsequent developments that include supply elasticities in the calibration process in Heckelei and Britz (2005) and Graveline (2016). In our case, the choice of the standard approach is justified by i) the lack of data on supply elasticities for the crops we consider. Concerning the yield function, we calibrated the model with a Mitscherlich-Baule specification as stated in Rosenzweig et al. (1999) who used the Mitscherlich-Baule relationship in the case of two inputs. In this paper, we use it for the single input case, i.e. water:

$$y_a = y_m(1 - exp^{-\beta_1(\beta_2 + ET_a)}) \qquad (14)$$

where y_a and y_m correspond to observed and maximum yields; ET_a corresponds to water applied to crops; β_2 is the soil residual water that we draw from the literature[9] and β_1 is computed as follows:

$$\beta_1 = -\frac{\ln(1 - y_a/y_m)}{\beta_2 + ET_a} \qquad (15)$$

The presence of y_m allows the input-yield relationship to respect the "plateau" feature of Von Liebig (Paris, 1992) – where a 'ceiling' on attainable yield is enforced, in accordance with agronomic reality.

The Lagrangian is written:

$$L = \sum_j [a_j(y_j(w_j) * p_j) - (\sum_i z_{ij} * c_{ij})] - \lambda_{land}(\sum_j a_j - A) - \lambda_{i \neq water}(\sum_j z_{ij} - totalinputi) - \lambda_{water}(\sum_j w_j - \overline{W}) \qquad (16)$$

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[9] See table B2 in the technical appendix.

First order conditions related to water input is:

$$\boldsymbol{\partial L/\partial w_j = a_j * p_j * \partial y_j(w_j)/\partial w_j - \lambda_{water} = 0} \qquad (17)$$

To derive the implicit 'demand' for water – we successively change the available water ($\overline{W}$) on the right-hand side of the water constraint, and observe how the shadow value of water ($\boldsymbol{\lambda_{water}}$) changes. This is empirically consistent with taking the derivative of the profit function ($\pi(\mathrm{p}, \mathrm{c})$) derived from the producer's profit maximization problem, with respect to the input price of water ($\boldsymbol{c_{water}}$), in order to derive the input demand function, according to Hotelling's lemma $D(\boldsymbol{c_{water}}) = -\,\partial\pi(p, \boldsymbol{c_{water}})/\partial \boldsymbol{c_{water}}$. Given the fact that water is not priced on the market as other purchased inputs are, and that the value must be derived implicitly from the solution of the constrained producer's overall optimization problem – our approach provides an empirically tractable way to obtain a demand for water that is consistent with the production technology and behavior that is observed in the data, and captured in our model. As Booker *et al.* (2012) describe in their overview of empirical methods for modeling water resource policy, this is a common approach when dealing with inputs not traded on markets, and whose use are observed as the result of management decisions, rather than being observed *ex ante*.

The inverse of the demand function in FCFA/ha per m^3 is written:

$$\lambda_{water}(w) = 8196.4w^{-0.442}, \text{ so } \mu = 8196.4 \text{ and } \theta = -0.442 \qquad (18)$$

Therefore the benefit function is obtained as follow:

$$B(w) = \int \lambda_{water}(w)dw \qquad B(w) = \frac{\mu}{\theta+1} w^{\theta+1} \qquad (19)$$

3.3. Simulated scenarios: rainfall scenarios and adaptation scenarios

We simulated two categories of scenarios: rainfall variability scenarios and adaptation scenarios. The former are composed of a reference rainfall scenario, a dry rainfall scenario and a wet rainfall scenario. Simulated climate scenarios are integrated into the hydroeconomic model through the equation of motion (1) to capture climate variability effect. Since farmers exclusively irrigate during the dry season using the quaternary sand aquifer, we assume that horticultural production is affected by climate variability through water availability which is captured within the hydroeconomic model. The farm production model captures the response of farmers to changing water availability under climate variability.

Adaptation scenarios are composed of i) autonomous adaptation defined by Leary (1999) as initiatives taken by private agents (here farmers) and ii) planned adaptation considered as policy-driven according to Smit et al (2001).

Based on these two categories of scenarios, we defined three composite scenarios:

a) ***A baseline scenario*** is composed of water availability (aquifer level) and groundwater use (withdrawals), land use and cropping pattern. This baseline scenario is simulated under the base rainfall scenario.

b) ***An Autonomous adaptation scenario*** that represents farmers' responses to water availability under climate variability. Farmers' responses are measured in terms of groundwater use behavior (water withdrawals) and changes in cropping pattern. This autonomous adaptation scenario is simulated in combination with the baseline and planned adaptation scenarios under the dry and wet rainfall scenarios.

c) ***A planned adaptation*** constitutes policy-driven water resources management scenarios. Here we tested an economic-oriented instrument: the introduction of a volumetric tax to motivate a reasonable use of the resource. This planned adaptation scenario is simulated under the base rainfall scenario.

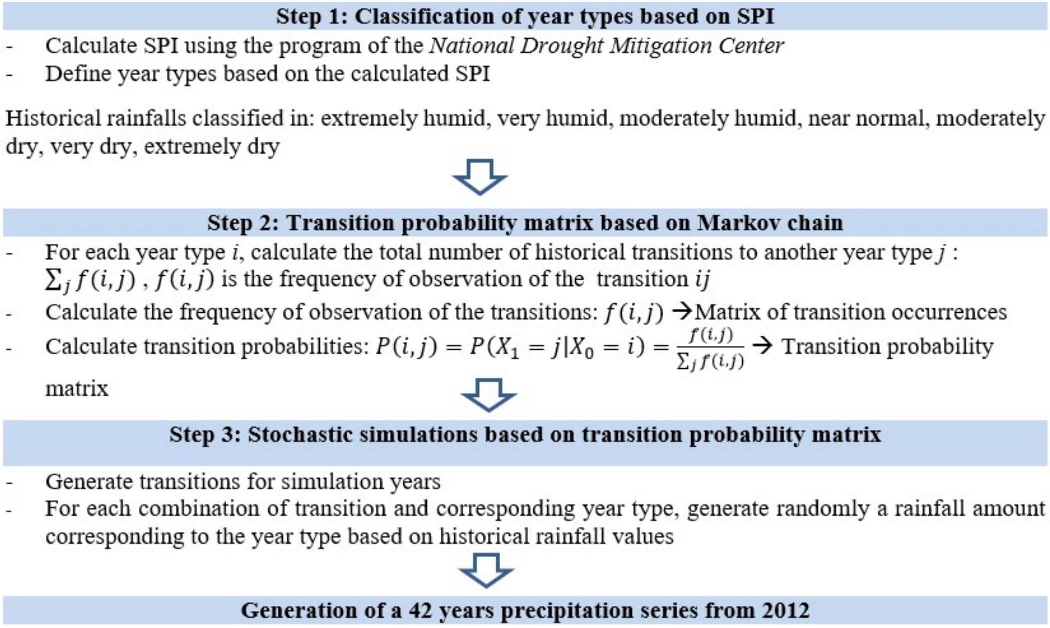
In the following sub-sections, we will detail the methods used to build scenarios.

3.3.1. Rainfall scenarios

Inspired by Safouane *et al.* (2016), we developed a stochastic rainfall generator based on Markov chains by using historical data for the period 1970-2011. Our methodological approach can be declined in three steps as summarized in figure 4.

The first step is to classify the year types using the standardized precipitation index (SPI) over 12 months (Mckee, Doesken, & Kleist, 1993) and rainfall data over the period 1970-2011. The advantage of using this index is its simplicity and the fact that it requires only rainfall data. We used the SPI program developed by the National Drought Mitigation Center[10] for calculating the index. According to this index, the years are classified as extremely humid, very humid, moderately humid, close to normal, moderately dry, very dry, extremely dry. The second step consists of calculating the probability transition matrix that reflects the probabilities of moving from one year type to another based on a first order Markov chain. The third step consists of performing stochastic simulations using the probability transition matrix.

Three scenarios are simulated over 42 years: i) a reference or base rainfall scenario which transition matrix is derived from historical data; ii) a dry scenario obtained by using the transition matrix of the base scenario with an increase of the transition probabilities of moving to dry years; iii) a wet scenario using the transition matrix of the base scenario with an increase in the transition probabilities of heading towards wet years. Although 42 years of rainfalls were simulated, we only do the analyses over a period of 10 years. Indeed, as suggested by Tanaka *et al.* (2006), long term studies should include changes in other variables such as population change. Simulation results as well as a comparison of statistical properties of simulated reference scenario and historical series are displayed in appendix C.



Step 1: Classification of year types based on SPI

- Calculate SPI using the program of the *National Drought Mitigation Center*
- Define year types based on the calculated SPI

Historical rainfalls classified in: extremely humid, very humid, moderately humid, near normal, moderately dry, very dry, extremely dry

Step 2: Transition probability matrix based on Markov chain

- For each year type i, calculate the total number of historical transitions to another year type j : $\sum_j f(i,j)$, $f(i,j)$ is the frequency of observation of the transition ij
- Calculate the frequency of observation of the transitions: $f(i,j)$ →Matrix of transition occurrences
- Calculate transition probabilities: $P(i,j) = P(X_1 = j|X_0 = i) = \frac{f(i,j)}{\sum_j f(i,j)}$ → Transition probability matrix

Step 3: Stochastic simulations based on transition probability matrix

- Generate transitions for simulation years
- For each combination of transition and corresponding year type, generate randomly a rainfall amount corresponding to the year type based on historical rainfall values

Generation of a 42 years precipitation series from 2012

Figure 4 : Steps for rainfall scenarios development
Source: Authors

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[10] http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx, accessed in March 2015.

3.3.2. Adaptation scenarios

Autonomous adaptation scenarios are endogenously accounted for in the different models. Indeed, since the models are behavioral, we consider that when a shock is imposed on them, the observed changes reflect farmers' responses to those shocks.

As for planned adaptation scenarios, according to economic literature on groundwater management (Griffin, 2006; Msangi & Cline, 2016; OECD, 2015; Ostrom, 1990), there are different policy options (ranging from tax and quota policies to water markets and collective management) to improve water availability in the long run for different users. Those policy options can be undertaken on the demand side (extractions) or on the supply side (recharge) or both of them. On the demand side, we tested, as stated previously, a tax policy on producers' water extractions as they are the main users of the resource and discussed the other cited management options. To estimate the tax, we introduced a tax parameter in the profit function of the hydroeconomic model. We then simulated different levels of taxes until we found the minimal level of volumetric tax from which the resource stabilizes over time. The following equation (20) shows the profit function with the tax τ:

$$\pi(x_t, w_{ag,t}) = SirrB(w_{ag,t}) - C(w_{ag,t}, x_t) - \tau w_{ag,t} \qquad (20)$$

As for the supply side measures, we did not test any specific measure. However, we computed the required annual additional recharge to stabilize the aquifer under the baseline scenario. The additional recharge was calculated by adding to the equation of motion (1) a "recharge" term that enables stabilization of the resource over time. We obtain the following equation:

$$x_{t+1} = x_t + 10^{-4} \frac{((1-\propto) w_{ag,t} + w_{NonAg})}{As_y} - \frac{\propto P_t * 10^{-3}}{s_y} + Recharge_t \qquad (21)$$

The resource stabilizes when:

$$x_{t+1} = x_t, \quad for\ all\ t ==> Recharge_t = \frac{\propto P_t * 10^{-3}}{s_y} - 10^{-4} \frac{((1-\propto) w_{ag,t} + w_{NonAg})}{As_y} \qquad (22)$$

4. Data

4.1. Farm model data: sampling, descriptive statistics and justification of the choice a representative farm

4.1.1. Sampling

Farm data was collected on a representative sample of 369 producers in the Niayes area in 2014. Producers were selected based on a two-stage stratified random sampling with two sampling units: villages and producers. We first stratified the Niayes area into three sub-areas based on physical differences to ensure that the sample will reflect the distribution of farmers in the south, center and north of the Niayes area. Based on population data of the Niayes from the National Agency of Statistics and Demography for the year 2012, we computed the share of each strata in the total population. Using the sample size that was fixed to 405[11] and the previously computed shares, we derived the size of each strata in the sample. We then sampled randomly 27 villages proportionally to the size of the strata. Finally, in each village, we sampled randomly 15 producers.

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[11] Note that the realities of the field combined with filling errors in the questionnaires brought us back to a database of 369 producers.

4.1.2. Sample characteristics and choice of a representative farm

The data mainly contains information on-farm activities (cultivated crops, inputs quantities and costs, revenues, labor) during the dry season and off-farm activities. The sample contains 97.29% of men and 2.71% of women with an average size of 2.65 hectares. The total irrigated area of the sample represents 10% of the total 10,000 hectares irrigated area of the Niayes. The main activity is irrigated horticultural production with mostly vegetables.

In the sample farmers are input-intensive with a broad use of mineral fertilizer (all farmers), organic fertilizer and pesticides. Labor is composed of family and paid labor that includes casual laborers and seasonal labor. The latter consists of "sourgas" hired on a seasonal basis and paid either by profit sharing, monthly or seasonally. Casual laborers constitute an additional source of labor that producers hire for specific farming operations (often plowing, harvesting and sometimes sowing). They are paid on a flat rate or daily basis. In this study, we consider only seasonal labor due to incorrectly measured data on casual labor.

As for irrigation, farmers in the sample use the quaternary sand aquifer which they primarily access through private wells. Other irrigation water sources include access through the water company (SDE). Farmers using the water company are entirely located in the south of the Niayes area (in the regions of Dakar and Thiès). Farmers extract water manually or with motorized pumps. In the case of manual extraction, irrigation is done manually with buckets or watering cans while in the case of mechanical/motorized extraction, irrigation is manual or mechanic. In total, only 24% of the sample uses mechanical irrigation technics among which 47% (which corresponds to 11% in the total sample) use drip irrigation, 5.62% use sprinkler irrigation (which corresponds to 1.5% in the total sample) and other technics that farmers did not report clearly. Table 1 summarizes the characteristics of the sample.

Table 1: Characteristics of the sample

	Farm characteristics	**Values**
Land use	Average cultivated land per farm (hectares)	2.65 (sd 2.7)*
	Cropping pattern (% of farmers cultivating the crop)	Onion (78.32), cabbage (45.26), tomato (41.19), sweet pepper (26), carrot (24.12), african eggplant (22), eggplant (22), pepper (9.49), potato (7.32)
	Share of area per crop over all area	
	Total area of the sample (hectares)	1000
Input and labor	Percent of farmers with family labor (unpaid)	96.48
	Percent of of farmers hiring paid labor (%)	Seasonal labor (66.12), temporary daily labor (59)
	Percent of farmers using inputs (%)	Mineral fertilizer (100), Organic fertilizer (88.88), pesticides (96.47)
Irrigation and extraction technology	Irrigation water sources (% of farms in the sample)	Dug wells (81.84), shallow wells[12] (5.96), Tube wells (8.94), Water company (1.89), Others (3.52)
	Well lift (meters)	Dug wells (8.04, sd 4.52) shallow wells (2.2, sd 0.70), Tube wells (10.38, sd 3.29)
	Water abstraction mode (% of farms in the sample)	Manual (60.16), Motorized (33.06) with electric or fuel pumps, Mixed (6.78)
	Irrigation technologies (% of farms in the sample)	Drip irrigation (11), sprinkler irrigation (1.5)
Total observations		369

**sd: standard deviation*

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[12] Shallow wells are called « céane » in the Niayes and are considered as traditional shallow wells from which water can be abstracted manually using a bucket without any need to connect it to a rope (Cissé *et al.*, 2001).

Source: Authors calculation

Although farms could have different characteristics along the Niayes, the data constraints on physical parameters prevent us from developing different representative farms. Therefore, we mainly consider one representative farm of the Niayes for modeling purposes. For the representative farmer, we only consider crops that are cultivated by more than 10% of the sample (see table 1). As for inputs, for each crop, we only consider inputs that are used by more than 40% to 50% of the sample cultivating that crop. The same reasoning is applied to labor. We could not obtain field-data on irrigation water use for the yield function of the farm model. Therefore, we estimated it by using the Doorenbos and Kassam (1979) yield-water relationship displayed in equation 23:

$$(1 - y_a/y_m) = k_y(1 - ET_a/ET_m) \tag{23}$$

Where, y_a, y_m, ET_a and ET_m have the same meaning as previously defined for the yield function. Based on this and knowing y_a, y_m and ET_m the quantity of water applied to each crop (ET_a) is obtained as follows :

$$\boldsymbol{ETa = Etm} * \left(\mathbf{1} - \frac{y_m - y_a}{y_m * k_y}\right) \tag{24}$$

Tables in appendix B1 indicate details on the data we used for the representative farmer and for the parameters in equation 24.

4.2. Hydro-economic model data

Hydroeconomic model data come from the literature and our own estimations. Data from the literature is mainly data on hydrologic parameters (infiltration rate and specific yields) in the area drawn mostly from doctoral theses undertaken by hydrologists and hydrogeologists (Gaye, 1990; Faye, 1995; El Faid, 1999; Tine, 2004). Data on groundwater withdrawals from the different agents, i.e. the Senegalese Water Company and rural borehole users, were obtained from the direction of hydraulics of the Ministry of Hydraulics and Sanitation and the Senegalese water company. As for farmers' extractions, as detailed in the methodology section, they were estimated using the estimated farm total water use and first order conditions from the hydroeconomic model in the baseline scenario. Table B3 in appendix B summarizes the parameters and data used for the hydroeconomic model and their sources. Concerning data on aquifer lift, we consider the median value of all well-types lift (see table 2).

Table 2: Aquifer lift data

Well types	Mean lift	SD*	Median
Dug wells	8.04	4.52	7
shallow wells	2.2	0.70	2
Tube wells	10.38	3.29	12
Ensemble	6.87	2.83	7

**SD: standard deviation*

Source: Authors calculation

4.3. Rainfall data

We obtained rainfall data from the national meteorological agency of Senegal (ANACIM) for the period 1970 to 2011 for the weather stations located in regions of Dakar, Thiès, Louga and St-Louis.

5. RESULTS

In this section we present our results on climate variability impacts and adaptation options on irrigated agriculture in the Niayes region of Senegal. The results are presented for five selected variables: aquifer lift, water withdrawals, land use and cropping pattern, farm income. The results for all these variables in the three defined scenarios (baseline, autonomous and planned adaptation scenarios) are summarized in table 6. Before presenting climate effect results, we found it important to first analyze the difference between the dynamic and myopic cases as we expose it in the following sub-section.

5.1. Comparing dynamic and myopic case results under the baseline scenario

We find that there is a small difference in aquifer levels and water withdrawals when moving from myopic to dynamic optimization cases although water availability is slightly increased in the latter case. Compared to the myopic case, there is only 0.09% average increase in the average cumulative present value of net benefits over the entire simulation period in the dynamic optimization case (from 93,032 thousand Fcfa[13] in the myopic case to 93,115 thousand Fcfa in the dynamic case).

Empirically, this small difference between the myopic and dynamic cases is known as the "Gisser and Sanchez" effect[14] that has been subject to multiple critiques. Koundouri (2004) suggests that this result depends on simplistic model specification and parameters such as the infiltration rate, water demand elasticity. Its controversies were then supported by a number of subsequent studies that have further refined hydro-economic models by taking into account aspects such as environmental damage (e.g. Esteban and Albiac, 2011), by analyzing the functional forms of the cost and net benefit from water extraction (e.g. Tomini, 2014) or by integrating technological progress through endogenous irrigation techniques (Kim, Fuglie, Wallander, & Wechsler, 2015). However, in our case some of the issues raised in those studies could not be integrated due to scarce data that prevented us from integrating ecosystem-level linkages to the groundwater hydrological flows in the Niayes region. Also, we could not endogenize irrigation and water extraction techniques as the data allowing to do so was not contained in the dataset, mostly the costs and benefits that would support farmers' decision to use such or such technology. The sensitivity analysis that we will perform will help us temper this limitation.

Since the difference between the myopic and dynamic cases is not very important, the results will mainly be presented in the myopic case except for the autonomous and planned adaptation scenarios for which, results will be displayed for the dynamic case. The reason for this choice is that since farmers' water extractions are lower in the dynamic case, we prefer using the latter to explore farmers' responses in order to avoid any overestimation of simulated adaptation strategies.

5.2. Impact of climate variability on groundwater availability: aquifer lift

To analyze the effect of rainfall variability on water availability, we compare the aquifer level in the reference rainfall scenario to aquifer levels in alternative rainfall scenarios (dry and wet) for the myopic case. Our results show that the drier the rainfall scenario considered, the

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[13] 1USD=~562 FCFA

[14] The "Gisser-Sanchez" effect refers to the conclusions reached by Gisser and Sanchez (1980) in their study of the Los Pecos basin, in which they stated that the gains to adopting centralized (optimal) management over myopic extraction of the groundwater resource were too small to justify any intervention.

greater the aquifer lift over the simulation period. Therefore, in a dry scenario, irrigation water availability is reduced and that effect is stronger when the drought is more severe. This is better illustrated in figure 5 that also shows that climate effect exacerbates over the years. Indeed, the difference in absolute value between the base scenario and alternative scenarios is on average 0.02% in the beginning of the period from reference rainfall scenario to dry scenario (respectively 0.1% from reference rainfall scenario to wet scenario) and 0.4% at the end of the period from reference rainfall scenario to dry scenario (respectively 0.5% from reference rainfall scenario to wet scenario). This suggests that considering a longer period would have more stressed the effect of climate variability. Furthermore, we also observe an upward trend in the depth of the aquifer over the 10-year period in the base and alternative rainfall scenarios with an increase of aquifer depth of approximately 0.73 meters for the dry scenario and 0.66 meters for the wet scenario compared to 0.69 meters for the reference scenario. Thus, withdrawals seem to exceed the rainfall recharge even with precipitation levels of about 500 mm on average over 10 years. We found that on average 13 millions of cubic meters of annual recharge (in addition to recharge from rainfalls) is needed to stabilize the aquifer over the simulation period in the baseline scenario.

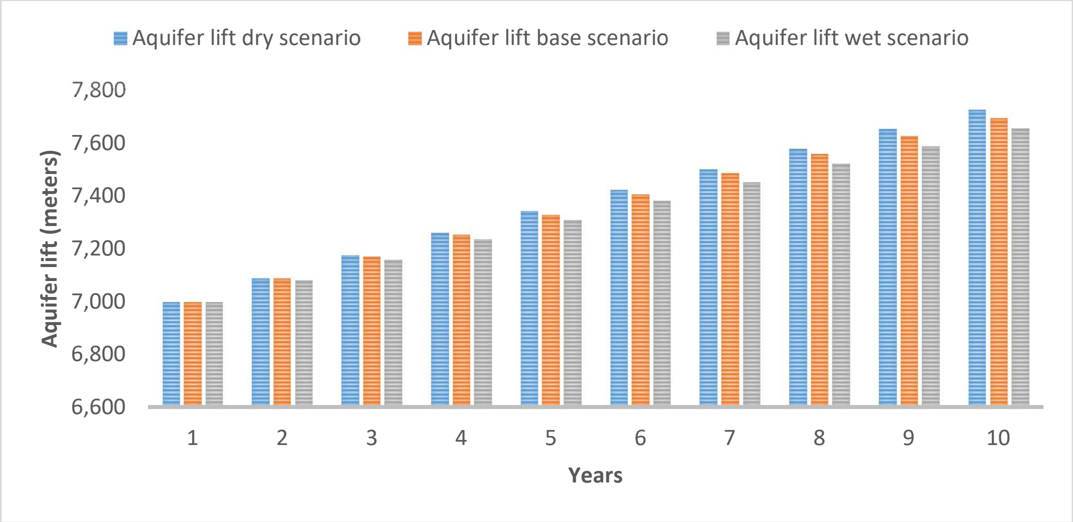

Figure 5: Comparison of aquifer lift under myopic extraction (dry, base and wet scenarios)

Source: Authors

5.3. Impact of climate variability and adaptation on water use behavior, cropping pattern and farm income

In the face of decreasing aquifer levels, farmers decrease their water extractions over the years (see figure 6) with a decrease of 6 millions of cubic meters in the baseline scenario, 6.3 millions of cubic meters in the autonomous adaptation scenario with dry rainfalls and 5.8 millions of cubic meters in the autonomous adaptation scenario with wet rainfalls. As with the depth of the water table, the difference (in absolute value) between the baseline scenario and the other scenarios increases over the years, about 0.04% in the first year from the reference scenario to the dry scenario (0.03% from the reference scenario to the wet scenario) and 1% in the last year for both scenarios.

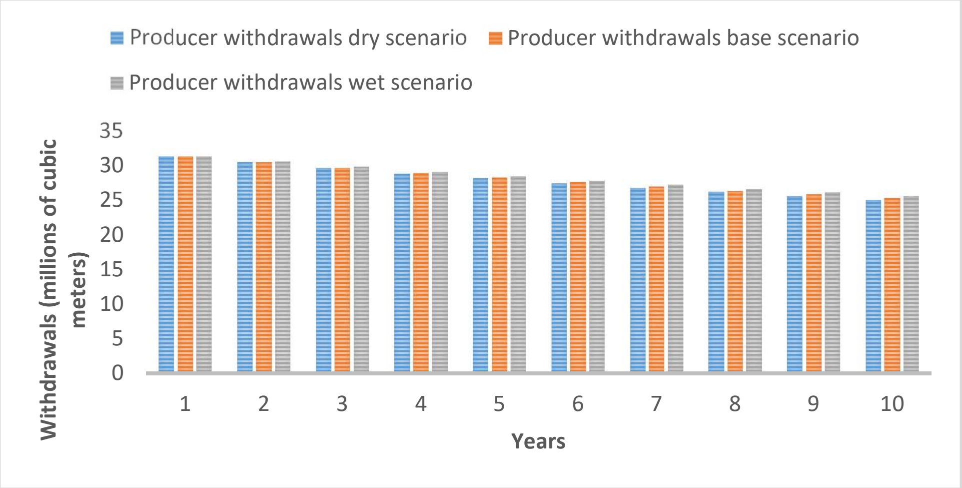

Figure 6: Comparison of farmers withdrawals under myopic extraction (dry base and wet scenarios)

Source: Authors

Concerning land use and cropping pattern, results show that in general, as the resource gets scarce, it is optimal for famers to decrease the area allocated to crops with slightly larger decreases in the autonomous adaptation scenario under a drier rainfall regime. We find that the area allocated to crops decreases more for crops with greater water requirements and lower net returns like carrot compared to crops with higher net returns (even when they have high water requirements) as shown in table 4. This drop in acreage results in a decrease in net producer income with slight differences between scenarios (see table 6) over the 10-year period.

These results suggest that the production of some horticultural crops (mostly low value crops) could be reduced in the long run under climate variability. Therefore, policies should incorporate better governance mechanisms for irrigation water resources to ensure their long-term availability for sustainable horticultural production in the Niayes. They should also investigate the possibility to extend horticultural production in other areas to reduce the pressure on water resources in the Niayes.

5.4. Agricultural water management options: tested planned adaptation

We tried a taxation policy to motivate farmers to preserve the resource by imposing increasingly an ad valorem tax on producers' water withdrawal. Taxes imposed vary between 0 (without tax) and 0.14 FCFA per cubic meter withdrawn. We find that the higher the level of the tax, the lower the withdrawals and the lower the aquifer lift. The level of tax required to stabilize the aquifer over time is greater than 0.1 FCFA per cubic meter. However, that would lead to a substantial reduction in farmers' withdrawals compared to the situation without tax. As a consequence, farmers would decrease the area allocated to crops. For some crops more than half of the initial area allocated is reduced as shown in table 4. This leads to a decrease in farmers' income of around 83% as shown in table 6.

Table 3: Land use under different levels of water availability and under taxation

Crops	Simulated area (t=1[15])	%change area allocation between t=1 and t=10 in dynamic case without taxation			%change area allocation between t=1 and t=10 in dynamic case under taxation (tax=0.1fcf/m^3)	Per hectar net return (x10^5fcfa/ha)	Water requirements (mm/ha)
		Base scenario (~340,6mm/an)	Dry scenario (~187mm/an)	Wet scenario (~507) mm/an)			
Onion	0.73	-18.59	-19.08	-17.84	-67.41	16.69	703.2
Carrot	0.51	-50.67	-51.41	-49.50	-98.10	8.05	1650
Cabbage	0.46	-3.05	-3.12	-2.95	-6.29	11.96	607.2
Sweet pepper	0.27	-5.44	-5.57	-5.25	-11.85	46.32	1201
Eggplant	0.40	-17.76	-18.23	-17.04	-63.55	16.80	1125.8
African eggplant	0.41	-10.42	-10.67	-10.02	-26.20	23.28	1125.8
Tomato	0.46	-2.26	-2.31	-2.18	-4.54	10.15	451.5

Source: Authors

Imposing such a tax requires having accurate information on the volume of groundwater being pumped by farmers, which is not yet well-documented for the Niayes area. It would also require that the revenue from the tax be redistributed to the farmers being charged in lump-sum, in order to maintain their overall welfare and to keep the policy revenue-neutral. The lack of information on producer's pumping can prevent from imposing the right resource management strategy – including a quota on pumped water. Therefore, the first step towards management should include rigorous measurement of farmers' withdrawals from the aquifer. More importantly, although being theoretically an option to manage groundwater resources, the application of a taxation policy on producers' side can lead – in the long term – to a drastic decrease in horticultural production in the Niayes that supplies more than half of the local market in horticultural products. This would neither be favorable to producers nor in line with political ambitions in the horticultural sub-sector. Consequently, even though the resource should be preserved over time, such a measure should be undertaken only if it allows preserving the resource without offsetting farmers' well-being. One of the venues would be to look for alternative production areas. It might even be better to look more broadly at overall water resource sustainability in Senegal (including surface water resources), and consider ways of sustainably exploiting available surface and groundwater to expand irrigation so that the country's horticultural (and other non-horticultural) production needs can be maintained.

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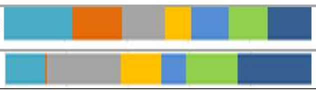
[15] See calibration results in annex B to compare with observed values.

Table 4 : Summary of results for the different scenarios and variables

	Change in aquifer lift—*x*--over time (meters)	**Change in water withdrawals over time** (cubic meters)	**Cropping pattern (%area used)** 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%	**Farm income (FCFA)**	**Change in farm income (%)**
Baseline scenario	+0.69	-6 millions	t=1 t=10 	5.515 millions* 4.096 millions	-25.7
Autonomous adaptation scenario (wet scenario case)	+0.66	-5.8 millions	t=1 t=10 	5.515 millions 4.151 millions	-24.7
Autonomous adaptation scenario (dry scenario case)	+0.73	-6.3 millions	t=1 t=10 	5.515 millions 4. 060 millions	-26.4
Planned adaptation scenario (tax=0.1fcfa/m³)	+0.003	473.77	t=1 t=10 	5.515 millions 925 120	-83.2

*Income simulated by the producer model the first year

■ Onion ■ Carot ■ Cabbage ■ Sweet pepper ■ Eggplant ■ African eggplant ■ Tomatoe

Source: Authors

5.5. Sensitivity analysis

In this section, we conduct a sensitivity analysis on three parameters of the hydroeconomic model: the infiltration rate, the discount factor, the elasticity of the demand function to see how our results on water availability would change as a result of a change in the value of those parameters. To avoid filling the paper with unnecessary figures and tables, for each parameter, we only report the changes we observe.

Sensitivity analysis on rainwater infiltration rate has been done considering rates between 0.4% and 20%. The analysis shows that higher infiltration rates imply a more available resource over time reflected by a lower aquifer lift and higher water withdrawals as shown in figures 7 and 8. A higher infiltration rate also induces a higher difference in water availability between wetter and drier situations.

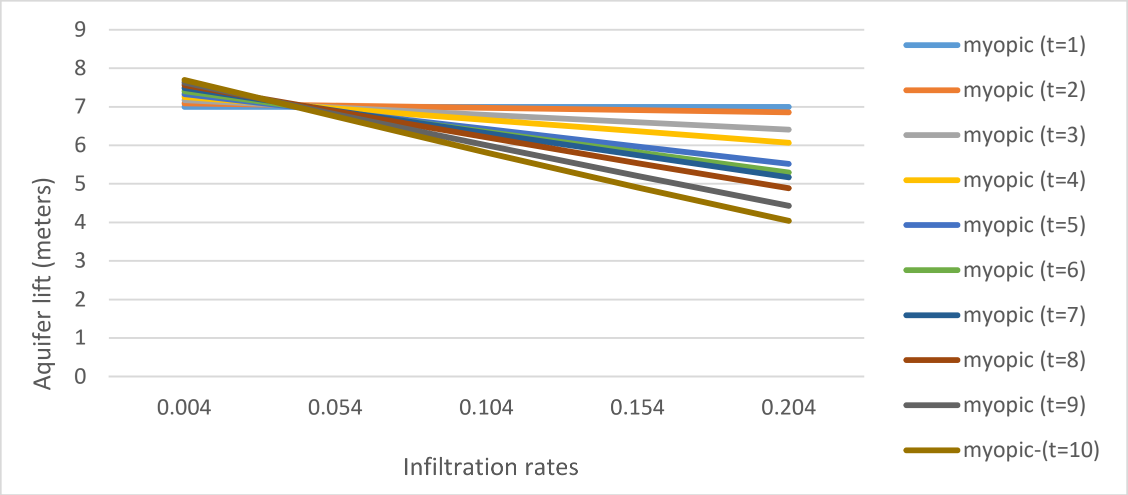


Figure 7: Sensitivity analysis—Aquifer lift under different levels of infiltration rate in the myopic case and baseline scenario

Source: Authors

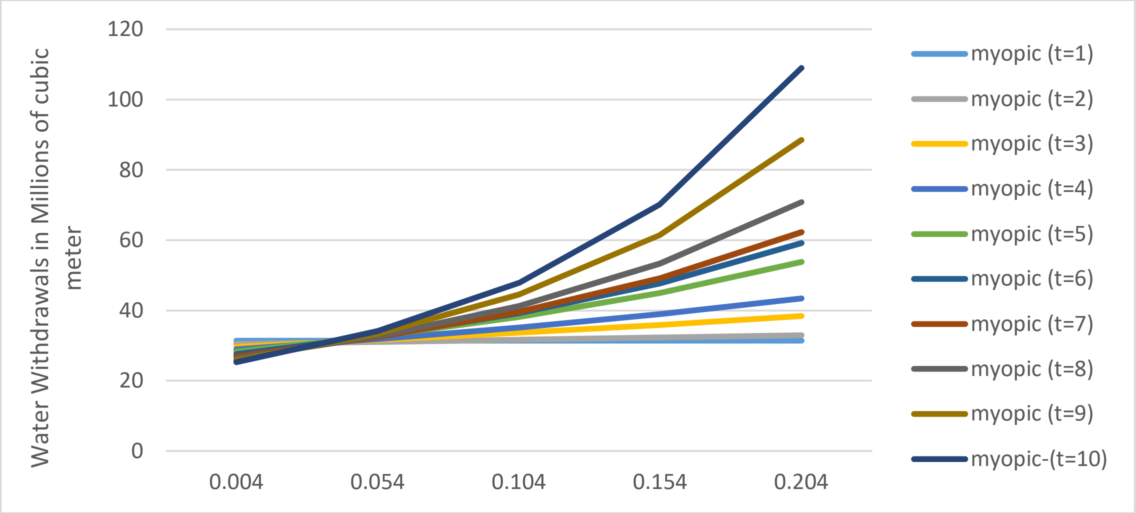


Figure 8: Sensitivity analysis— producer withdrawals under different levels of infiltration rate in the myopic case and baseline scenario

Source: Authors

As for the discount factor, we run the model with lower interest rates ranging from 6.5% to 2.5%; therefore, a higher discount factor $(\frac{1}{1+i})$. It is important to note that the myopic case is not affected by a change in the discount factor due to the fact that the future is not integrated in the myopic problem. We find that, farmers' water extractions in the dynamic case are smaller in all periods with lower interest rates as shown in figure 13. Thus, the difference between myopic and dynamic cases becomes more important. This can be explained by the fact that the higher the discount factor, the higher the present value of future net revenues. As a result, farmers value the availability of the resource in the future and thus decrease their withdrawals in the dynamic case which improves the availability of the groundwater reflected in a lower aquifer lift with lower interest rates (see figure 9). We further find that changes in the discount factor do not affect significantly the difference in water availability between rainfall scenarios.

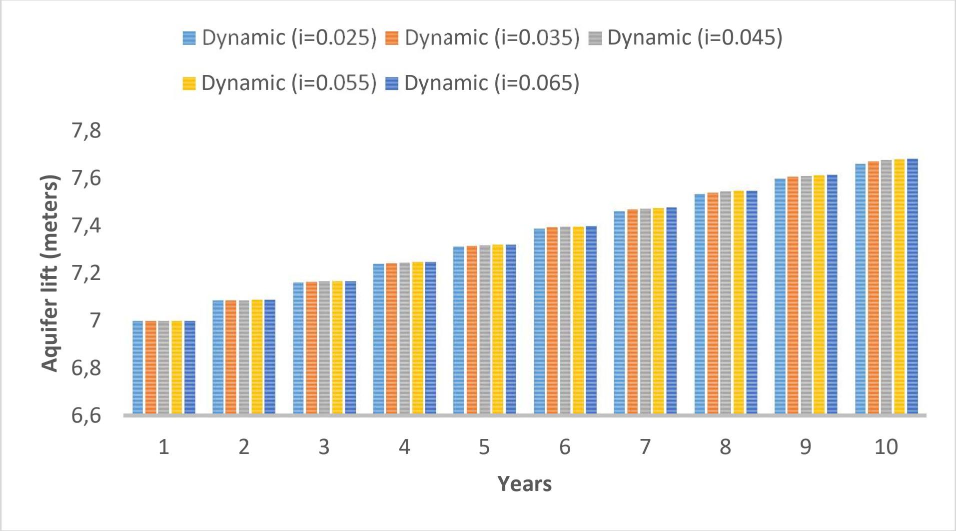


Figure 9: Sensitivity analysis--Aquifer lift under different levels of interest rate in the myopic case and baseline scenario

Source: Authors

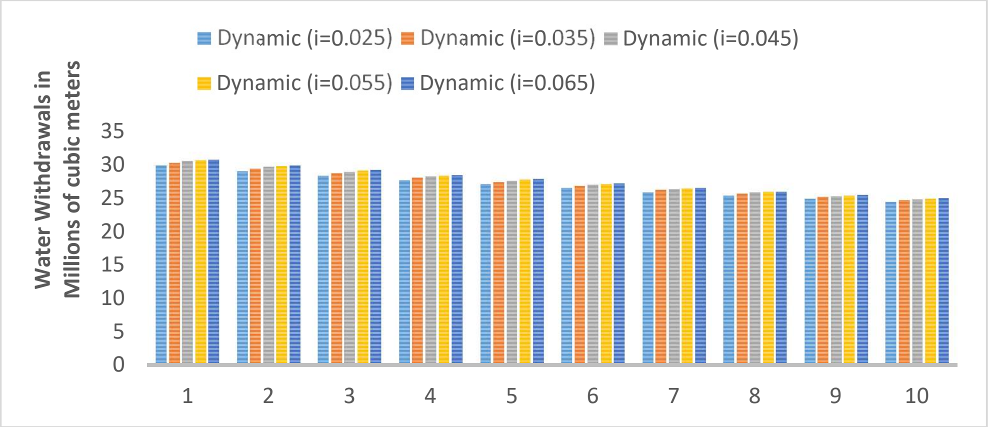


Figure 2: Sensitivity analysis— producer withdrawals under different levels of interest rate in the dynamic case and baseline scenario

Source: Authors

Concerning the elasticity of the demand function, we imposed a lower elasticity of -0.15 and a higher elasticity of -0.80. We note that the more the demand is inelastic (the elasticity tends to 0 in absolute value) the greater the difference between the withdrawals in the first and last years (the decreasing trend in water availability remains unchanged) as shown in table 7.

Table 5: Water withdrawals under elastic and inelastic demand

	Water withdrawals with elastic demand (elasticity =-0.8)		**Water withdrawals with inelastic demand (elasticity =-0.15)**	
Years	Dynamic ($x10^6$ m^3)	Myopic ($x10^6$ m^3)	Dynamic ($x10^6$ m^3)	Myopic ($x10^6$ m^3)
1	28.72	31.40	31.38	31.40
2	28.32	30.89	28.81	28.83
3	27.98	30.45	26.81	26.83
4	27.64	30.01	25.06	25.08
5	27.33	29.61	23.65	23.66
6	27.00	29.20	22.28	22.29
7	26.68	28.80	21.05	21.06
8	26.38	28.43	20.02	20.03
9	26.10	28.08	19.16	19.16
10	25.83	27.75	18.37	18.38
Difference	-2.88	-3.65	-13.01	-13.02

Source: Authors

Overall, these sensitivity analyzes show that the choice of rainwater infiltration rate is an important element in analyzing the effect of rainfall variability on the availability of groundwater resources for irrigation in the Niayes. Indeed, the higher it is, the more the difference between rainfall scenarios is important. The other elements (discount factor and water demand elasticity) have a greater impact on producers' water withdrawal behavior and so affect the depth of the aquifer; however, they do not affect much the differences in water availability between rainfall scenarios nor the overall trend of results. These results confirm the critiques of simulation-based analyses put forward by Koundouri (2004).

6. Discussion

6.1. Water availability under climate variability

Our results on water availability under climate variability over time is consistent with earlier literature in the Niayes. Aguiar *et al.* (2010) studied the interannual past evolution of the quaternary sand aquifer between 1958 and 2002 and compared the evolution of aquifer levels during wet periods (1958-1970) and during dry periods (from 1972) in some localities of the Niayes. They found that the water table remained high during wet periods and observed the most significant drops in water table during the droughts of the 1970s and 1980s.

Concerning the insufficient recharge, Dasylva and Cosandey (2005) analyzed the water budget of the quaternary sand aquifer in the south of the Niayes (Dakar) under different rainfall scenarios and showed that with a normal or deficit rainfall, the water balance is negative and only becomes positive from excess rainfall averaging 700 mm per year. Thus, they find that recharge from rainfalls is insufficient to ensure effective re-supply of the aquifer when annual precipitations are lower than their levels during wet periods (before 1970). In our case, we find that even in a wet scenario situation (about 507mm), the resource becomes more scarce over time.

Regarding the magnitude of the increase of the aquifer lift over the ten years we simulated, Aguiar *et al.* (2010) found that over the period 1958-1994, the water table fell by nearly 0.51 meters on average every 10 years. In the same way, our results show that the water table will continue to fall on average of the same amplitude or more depending on rainfall levels over a given 10-years period. This decrease of the water table could have implications on water quality. Indeed, with climate change, it is predicted on the coastal zone of Senegal a sea level rise of 20 cm by 2030 and 80 cm by 2080 compared to a rise of only 3 cm between 1990 and 2010 (World Bank, 2014). An average continuous drop in the aquifer level of 0.60 meters (60cm) over 10 years increases the risk of saline intrusion that would be detrimental to horticultural production in the coastal Niayes.

Also, increasing aquifer lift can have implications on irrigation technology use. Indeed, as argues Sekhri (2013, 2014) who studied water related issues in some Indian villages, as long as the depth of the groundwater is not greater than 8 meters below ground, water can be extracted using surface pumps. However when the depth is more than 8 meters from the surface, farmers need to use costlier submersible pumps for water extraction.

6.2. Farmers response to water availability

Results on farmers' autonomous adaptation to decreasing water availability are somehow similar to other results in other contexts. We compare the results with studies in other contexts because adaptation to aquifer availability in the Niayes area has been poorly studied. In India, Sekhri (2013) analyzed the impact of a decline in groundwater and finds that a drop of one meter of the water table over a year causes a drop in production, especially for more water demanding crops. In the same way, in Spain, Esteve *et al.* (2015) used an integrated hydro-economic model for surface water and found that when available water decreases in the face of climate change, producers change their cropping pattern and their income declines. Moreover, Heidecke (2010) showed that (by analyzing survey data) in Morocco, when there is water shortage due to groundwater decline, the main reaction of producers is to reduce the area under cultivation.

It should be noted that the only strategies available for producers in our production model are the reduction in area under cultivation and the change in cropping pattern (among crops taken into account). These strategies, included here, assume that when water availability decreases, producers limit themselves to the amount of water available and adapt accordingly. For example a producer who grows one hectare of onion will not continue to cultivate one hectare of onion when available water drops; but will cultivate an area that he/she can irrigate with available water. However, based on our field experiences and literature (Heidecke, 2010; Sekhri, 2014), in addition to strategies related to acreage decrease and changes in cropping pattern, producers can also adopt other strategies that enable them to extract more water by increasing their water pumping capacity and therefore continue to cultivate the same areas (or even more) than before climate shock. For instance, Heidecke (2010) finds that another producers' reaction is to increase the use of the aquifer for irrigation reflected by the increase in the number of motor pumps and the drop in phreatic levels in the years of drought.

Currently, our model does not allow for such adaptation strategies that require the adoption of new water extraction technologies which can overestimate the impact on agricultural production. However, these strategies could negatively affect net income because they have implicit costs. This increasing cost will arise either from the increasing energy cost of pumping groundwater from a lower depth and/or from the fact that a falling groundwater table means that additional capital costs might need to be incurred in order to deepen the wells or to install higher capacity pumps to access the water. It is therefore difficult to conclusively state their possible impact on production without additional data on those costs. It should also be remembered that some strategies that improve water access could, in turn, negatively affect the groundwater resource and lead to increased water scarcity over time. Indeed, according to (Berbel, Calatrava, & Garrido, 2007), "Investment in irrigation technologies has ambiguous effects [...]. Negative effects result from the fact that changes in technology may induce new crop patterns and increase total water consumption". Also, integrating technological progress would require allowing the possibility of endogenously adopting new extraction technologies before choosing the amount of water to be extracted (given the chosen technology) which induces a hydroeconomic model with two decision variables (technology adoption and water extraction levels). These methodological limitations will be addressed in future work.

6.3. Planned adaptation results

Results on water pricing management strategy can be compared to what has been found in the literature in other contexts. Indeed, (Aidam, 2015) did an analysis of the impact of price mechanisms on the water demand for farmers in Ghana and showed, using the example of large producers, that setting water prices leads to a decrease in the water consumption of producers who reduce the production of high water demanding crops to cultivate crops that require lower water consumption. This negatively affects producers' incomes. Also (Berbel & Gomez-Limon, 2000) analyzed the impact of setting water prices in three irrigated areas in Spain. They found that water prices as the only instrument to control water use is not a valid instrument to reduce the demand for agricultural water in a significant way. Indeed, water consumption does not decrease until prices reach a level that significantly reduces producers' income and labor use. They also found that, for the locations considered, when price mechanisms are used to reduce water consumption, a 40% reduction in producers' income is required to drop water demand significantly which leads to a reduction in the number of crops. Finally, when water consumption decreases as a result of substituting high water demanding crops, there will be a decline in the utilization of the labor force at the farm level and at the processing industry level.

These results are in line with what we found on taxation impact. However, in our results, the decrease in farmers' income is higher as discussed in the results section.

7. Conclusions and research agenda

This modeling framework is a first step towards a better representation of groundwater use in a context of climate variability and change and multiple usage of the quaternary sand aquifer in the Niayes area of Senegal where irrigated horticulture is the main agricultural activity.

Modeling results show that under both myopic and forward-looking cases rainfall variability affects water availability in the Niayes area. In the period 2014-2023, under different rainfall scenarios, we found that the dryer the climate, the lower the groundwater table resulting in farmers reducing their water withdrawals. Results also highlight low net returns gains between myopic and dynamic optimization cases known as the Gisser and Sanchez effect which could be explained here by the structure of the model that treats the groundwater underlying the Niayes region as belonging to one big reservoir, rather than several connected ‘compartments’. Also, we consider non-agricultural users’ withdrawals exogenous which led us to only account for on-farm benefits while there are also off-farm benefits that a social planner would consider. Therefore, further developments should be performed to accurately endogenize non agricultural users’ behavior to see how it affects results. Also, as develops Koundouri (2004), the choice of parameters such as the elasticity of water demand, the infiltration rate is important in model design. Moreover, as suggests Esteban and Albiac (2011), there might exist ecological and environmental aspects that also affect groundwater availability that we are missing within our model specifications. We also found that the resource is being depleted over time, in all climate scenario considered (even though the effect is stronger in dryer scenarios) and whatever the degree of myopia or foresight exercised by the decision-maker. This shows that rainfall recharge does not cover water extractions that mostly come from farmers. Our model shows that an average additional annul recharge of 13 million cubic meters is required to stabilize the aquifer over the 10 years simulation period.

We further found that as a response to decreasing resource availability over time, in all the scenarios considered, it is optimal for farmers to decrease the area allocated to crops by the end of the considered period. Greater decreases of area are noted in a drought situation. Also, crops with low returns and high water requirements are subject to greater area decreases. Therefore, resource depletion might lead to significant decrease in irrigated area over time – either due to the effect on pumping costs and accessibility or through the effects of saline intrusion into the aquifer – which would threaten long-term horticultural production sustainability in the Niayes.

To ensure sustainability of the resource, we tested a demand-side instrument, i.e. a volumetric tax, as a resource management policy measure and found that the minimal level of tax per cubic meter withdrawn required to stabilize the aquifer over time is 0.1fcfa. However, such a taxation measure would lead to a drastic decrease of farmers’ withdrawals, area allocated to crops and income. Ensuring resource sustainability being as important as meeting demand on horticultural products, a tax on producers’ side should be carefully investigated so as to avoid a drastic decrease in production in the long-run.

Different alternative demand options (a quota, water markets, collective action) and supply side measures that we did not test exist. A quota-based policy would lead to the same results (if successfully implemented) as the tax in terms of water extraction decreases. We did not test it – recognizing that, as a tax, it would be difficult to administer in this region. However, it should be noted that a quota may have less negative effects on producers' incomes. In addition, empirical studies have shown that a tax could lead to more reluctance from producers than a quota (Montginoul & Rinaudo, 2009). Concerning water markets, they are feasible when users have well-defined property rights (Griffin, 2006) that they can exchange in a market. This type of solution could also be difficult to generalize in the Niayes context, given the type of management institutions that currently exist, and the absence of efficient mechanisms for the producers to communicate their willingness to buy and sell water. As for the possibility of engaging in the collective management of groundwater, we cannot test it here because it requires taking into account the characteristics and interactions between all the stakeholders and illustrating the bargaining possibilities that might lead to a collectively cooperative outcome. Recent work in India by Meinzen-dick *et al.* (2017) describes the applications of experimental games to explore the willingness to engage in collective action with regards to the groundwater resource, and the effect that increasing awareness of pumping externalities on the part of the players has on this willingness-to-engage. Such an approach would be useful in exploring the potential for organizing such an institutional framework in the context of the Niayes, and will be considered for future work. In the methodological approach chosen here, we treat the institutions as exogenous and focus on the dynamics of depletion and the implications that it has on the agricultural economy.

Supply-side measures (like rainwater harvesting for aquifer recharge enhancement) can be alternatives to demand-side measures or complement them. However, the difficulty that can be encountered is related to the high investment costs and their affordability. Most likely, external development aid and lending would have to be mobilized for this kind of scheme, and should be part of the discussions with external donors on Senegal's overall investment strategy for the irrigation sector.

Finally, we noted several model limitations that included the non-integration of technological progress (i.e. making irrigation and extraction technologies endogenous), which prevented us from accounting for a broader range of adaptation strategies. However, these are currently being investigated through a mixed-method approach (quantitative and qualitative tools) through the use of forum-theatre that enables us to engage more dialogue with farmers and enhance management options. Nonetheless, the modeling framework and the findings from this study provide a basis for further research on climate impact on irrigation water availability and agricultural water management in West African agriculture.

ACKNOWLEDGMENTS

This research was supported by the Bureau of Macro-economic Analyses of the Senegalese Institute of Agricultural Research and by the Ministry of Foreign Affairs of Finland, through the *FoodAfrica* project.

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TECHNICAL APPENDIX

In this technical appendix, we explain in more detail (for the benefit of the reviewers and the interested readers) the specification of several key parts of the analytical framework – namely:

a) The method for approximating the infinite-horizon, carry-over value function for the dynamic programming problem;
b) Information on the data and the calibration of the farm model;
c) Comparison of simulated and observed rainfalls

A. Complementary methodological material

A1. Approximating the value function

To estimate the carry-over value function that defines the infinite-horizon dynamic programming resource management problem, we employ an approximation technique using an n-degree Chebychev polynomial. Such 'projection methods' for solving dynamic programming problems are described in (Judd, 1998).

There are a number of alternative approaches to numerically approximating the carry-over value function $V(x_t)$[16] that is used to solve the infinite-horizon DP problem (as described in Judd (1998)). In our paper we use a numerical approximation method that uses a n$^{\text{th}}$ order Chebychev polynomial – which is one of several possible 'orthogonal polynomial' approximations that can be used (Judd, 1998).

In this approach, the function is evaluated over the domain of possible values that the state variable can attain, and is numerically computed at specific 'nodes' within the domain – whose number define the order of the polynomial approximation. These Chebychev nodes provide the points from which the numerical value of carry-over into the next period of the dynamic programming problem can be interpolated to cover the entire domain of the value function. The number of nodes of approximation can be increased to any desired number in order to improve the numerical 'fit' of the value function – but at the cost of additional computational burden. This is described further in (Howitt *et al.*, 2002).

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[16] Hubbard et Saglam (sd.)

— Chebychev nodes

For m nodes, the k^th node of the Chebychev function is written as: $z_k = -\cos(\pi(2k-1)/2m)$, k = 1, ..., m, $m \geq n+1$.

z_k falls within the closed interval [-1 , 1].

We note that the values of the state variable do not necessarily fall within this restricted interval – but lie within a more general range of values [a , b] where a and b represent, respectively the minimum and maximum values of the state variable

The mapping of the nodes of the Chebychev polynomial (x_k) from the interval [a,b] onto the [-1,+1] domain is done with this relationship :

$$z_k = \frac{2(x_k - a)}{b-a} - 1$$

— The Chebychev polynomial terms

After having defined the nodes of the Chebychev polynomial, we then approximate the value function at defined nodes over the domain of the state variable, with the polynomial function, which is defined as : $V(x) = \sum_i a_i \Phi_i(x)$

where

a_i is the coefficient of the i^th Chebychev polynomial term

the polynomial terms can be written as: $\Phi_n(x) = \cos(n * \cos^{-1}(x))$

Using a recursive scheme, we can write out the terms of the Chebychev polynomial as:

$$\Phi_0(x) = 1$$
$$\Phi_1(x) = x$$
$$\Phi_3(x) = 2 * x\,\Phi_2(x) - \Phi_1(x)$$
$$\vdots \qquad \vdots$$
$$\Phi_n(x) = 2 * x\,\Phi_{n-1}(x) - \Phi_{n-2}(x) \quad for\ n\ terms$$

Over the interval $[-a, b]$, $a_i = \frac{\sum_{k=1}^{n} V(x_k)\Phi_i(z_k)}{\sum_{k=1}^{n} \Phi_i(z_k)\Phi_i(z_k)}$

$$V(x) = \sum_i a_i \Phi_i\left(2\frac{x-a}{b-a} - 1\right)$$

Value function iteration

Following this approach, we can solve the Bellman equation of the infinite-horizon dynamic programming problem by taking the following steps:

i) Give an initial estimate of the carry-over value function that is defined on the right-hand side of the Bellman equation for the DP problem

ii) Calculate the left-hand side value of the Bellman equation using the mapping relationship $TV(x_k) = f(x_k, c_k) + ß \sum_j V(x_k)$ which depends upon the intial 'guess' of the carry over value V(x) that was done in the first step and the optimal value of the benefit function for the DP problem. This gives you a new value for V(x) using the contraction mapping V=TV which is applied to the next iteration, if the convergence of sequential estimates of V(x) to a stable value has not been achieved.

iii) Verify if the difference$|TV - V| < \varepsilon$, where ε *is sufficiently small*

- ✓ If yes – then the infinite-horizon value function that defines the Bellman equation has been found
- ✓ If not, then we return to the step ii) and repeat the procedure until the condition described in iii) has been satisfied

In this approach, we rely upon the "contraction mapping theorem" to guarantee convergence to a stable value of V(x) for any initial guess.

B. Information on the data and the calibration of the farm model

B1. Farm model data

Table B1: Farm production model data

		Crops						
		African eggplant	Eggplant	Carrot	Sweet pepper	Tomato	Cabbage	Onion
Cultivated area (ha)	Mean	0.41	0.4	0.58	0.27	0.46	0.46	0.73
	Median	0.25	0.25	0.36	0.25	0.25	0.25	0.5
Yields (kg/ha)	Mean	10833	18045	12105	10010	10478	9948	10566
	Median	7040	16000	9933	6100	6560	7178	9333
Crop prices (Fcfa /kg)	Mean	243.64	117	115.01	489.59	121	148.91	239.31
	Median	200	111.11	101.72	300	97.56	113.2	235
Seeds (kg /ha)	Mean	0.22	0.26527	2.74789	0.19836	0.25559	0.56213	2.21061
	Median	0.250	0.300	3.460	0.200	0.300	0.650	2.614
Seed cost (Fcfa /kg)	Mean	108001	119001	23000	252001	230001	158000	55001
	Median	100000	100000	24000	209000	160000	145001	58000
Mineral fertilizer (urea) (kg /ha)	Mean	278.60	501.67	203.29	266.94	148.05	290.73	191.98
	Median	120.92	248.25	84.96	180.03	109.42	108.51	95.38
Urea cost (Fcfa /kg)	Mean	289.54						
	Median	280						
Mineral fertilizer (10.10.20) (kg /ha)	Mean	355.59	437.1 8	268.46	266.039	207.90	283.74	246.27
	Median	195.28	372.38	118.94	180.03	109.42	108.51	136.26
Unit cost of 10.10.20 (Fcfa /kg)	Mean	273.16						
	Median	250						
Organic fertilizer (kg /ha)	Mean	3267	4003	4399	2044	2776	1744	2394
	Median	1292	1241	1639	1216	1055	1046	1362
Organic fertilizer cost (Fcfa /kg)	Mean	33.67						
	Median	31.10						
Herbicides (l/ha)	Mean	3.66						
	Median	2.72						
Herbicides Cost (Fcfa/l)	Mean	8002						
	Median	8000						
Seasonal labor cost	Mean	138349						

Source: Authors

Table B2 : Additional parameters and data for the farm model

	Parameter	Value	Source
	Soil residual water	100mm	Fall (2012)
Farm model right hand side value of constraints	Total area cultivated (A)	3.31ha	
	Totalfamilylabor	21 person/season	Our data
	Totalpaidlabor	6.21 person/season	Our data

Table B3: Data from literature and research centers to calculate crop water use

Crops	Crop water requirements --ETm (m^3/ha)	Maximum Yields (y_m)--(kg/ha)	Yield response to water (k_y)
African eggplant	11258	50000	1,37
Eggplant	11258	50000	1,37
Carrot	16500	35000	0,82
Sweet pepper	12010	50000	1,1
Tomato	4515	50000	1,05
Cabbage	6072	40000	0,95
Onion	7032	35000	1,1

Data source: Crop water requirements (from Senegal's Center for the Development of Horticulture (CDH)) ; Maximum yields (from PADEN website[17]*, we assumed a threshold of 50000 for the remaining crops due to lack of offically updated data). Yield response to water (from Doorenbos and Kassam (1979) for all crops except carrot from Carvalho et al. (2016) and eggplants from Lovelli et al. (2007)).*

B2. Calibration results

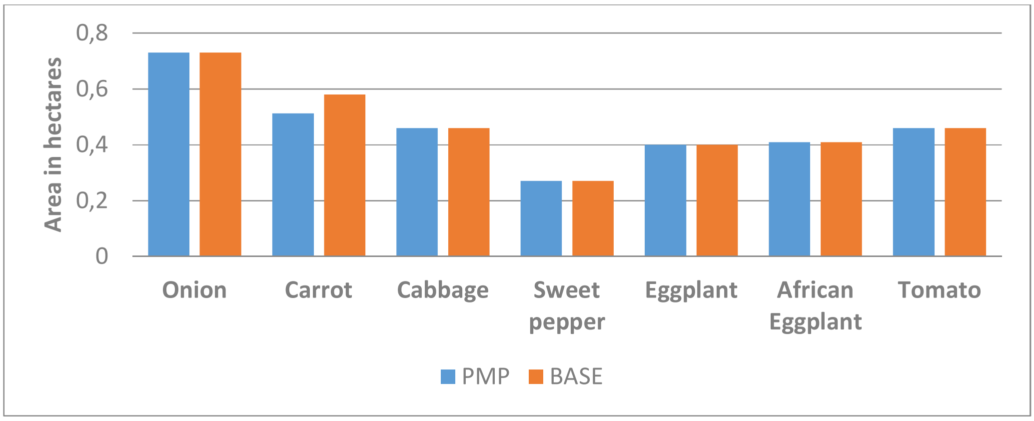

Figure B1: PMP calibration results (area)

Source: Authors

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[17] PADEN is a project for the development of the Niayes region. It is a project of the Ministry of Agriculture (2013), see: http://www.paden-senegal.org.

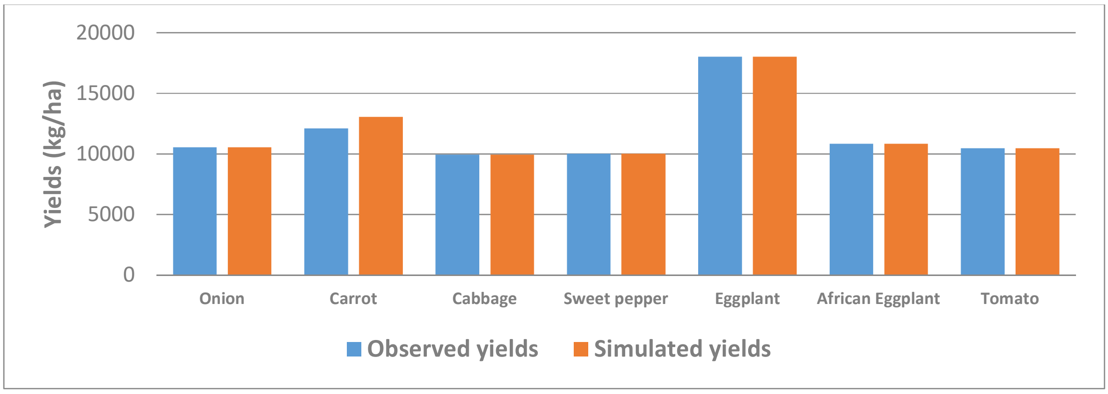

Figure B2: Calibration results (yields)

Source: Authors

B3. Hydroeconomic model data

Table B4: Parameter values for the hydro-economic models

Parameter	Value	Data source
Infiltration rate	0.4%	Tine (2004)
Elasticity of the demand function	-0.442	Our farm model
Constant of the demand function	8196.4	Our farm model
Discount rate	7.5%	CNCAS
Specific yield	0.15	Dasylva and Cosandey (2005)
Total irrigated area in the Niayes	10000 ha	Faye *et al.* (2007)
Aquifer lift	7m	Sample data
Water extraction from non-ag (water company and rural boreholes sector)	1374495m^3	Ministry of hydraulics and sanitation and the Senegalese water company
Area covered by the quaternary sand aquifer	2300 km^2	Aguiar *et al.* (2010)

Source: Authors with data from literature

C. Historical and simulated rainfalls: a comparison

Table C1: Simulated rainfalls

Years	Rainfalls in base scenario (mm)	Rainfalls in dry scenario (mm)	Rainfalls in wet scenario (mm)
1	163.3	209.225	462.35
2	389.325	163.3	569.725
3	318.05	209.225	479.925
4	479.925	209.225	569.725
5	259.85	166.225	471.65
6	192.325	209.225	569.725
7	318.05	163.3	439.975
8	458.95	166.225	569.725
9	439.975	182.725	458.95
10	386.275	192.325	479.925
Mean (mm)	340.6	187.1	507.17
Coefficient of variation	0.322	0.112	0.108

Source: Authors

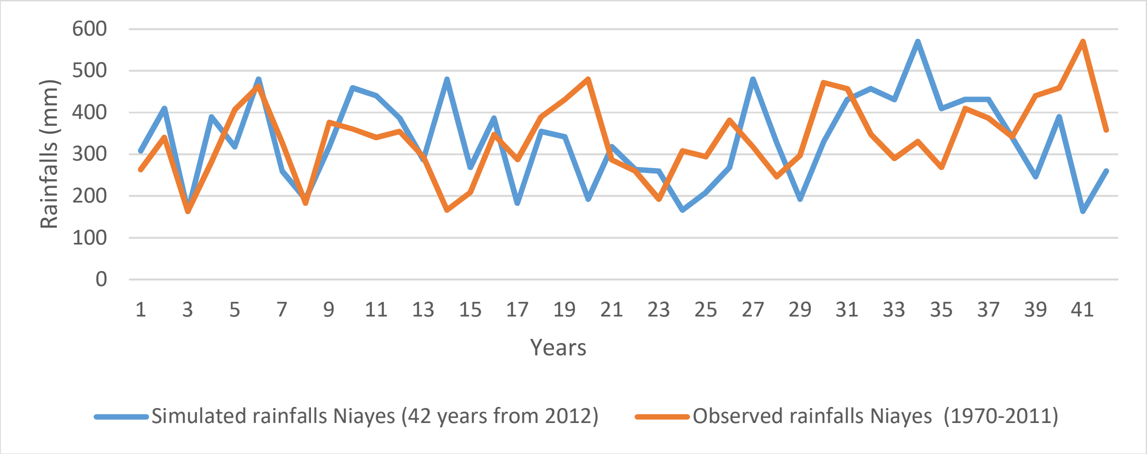

Figure C1: Simulated rainfalls vs. Observed rainfalls

Source: Authors

Table C2: Comparison of statistical characteristics of observed and simulated rainfall series

Rainfall time series	Mean (mm/year)	Coefficient of variation
Simulated rainfalls (42 years from 2012)	333.10	0.31
Observed rainfalls (1970-2011)	337.55	0.27

Source : Authors